Towards an Improved Mapping of Evapotranspiration in Semi-Arid Regions

MUSTAFA GÖKMEN[1], CHRISTIAAN VAN DER TOLL[1], ZOLTÁN VEKERDY[1], WOUTER VERHOEF[1], OKKE BATELAAN[2], HASAN Z. SARIKAYA[3]

1 *Department of Water Resources, Faculty of Geo-Information Science and Earth Observation (ITC), University of Twente, Enschede, The Netherlands* (gokmen13523@itc.nl)
2 *Department of Hydrology and Hydraulic Engineering, Vrije Universiteit Brussel, Belgium*
3 *Department of Earth and Environmental Sciences, K.U.Leuven, Belgium*
4 *Ministry of Environment and Forestry of Turkey, Ankara, Turkey*

Abstract In drylands, evapotranspiration is mainly limited by soil moisture, but current surface energy balance models do not directly make use of this fact. We tested the single-source energy balance model SEBS in a semi-arid region and showed that SEBS is significantly overestimating the evaporative fraction for sparsely vegetated drylands. As an alternative for such conditions, we derived an empirical function of soil moisture, temperature gradient and NDVI, which performed significantly better. This was then integrated with the evaporative fraction output of SEBS for an improved mapping of evapotranspiration in a semi-arid region. Ground measurements of the evaporative fraction from five Bowen ratio energy balance systems were used first to test SEBS and then to calibrate the empirical equation. The resulting method uses remote sensing data and in situ air temperature measurement.

Key words evapotranspiration; evaporative fraction; Bowen ratio; remote sensing; SEBS; soil moisture.

1. INTRODUCTION

Remote sensing (RS) of the surface energy balance has been a major solution for assessing spatial distribution of evapotranspiration (ET) in the last decades. One of the physically and RS based models is the Surface Energy Balance System (SEBS) by Su (2002). SEBS combines optical and thermal RS with meteorological data to calculate the turbulent heat fluxes. SEBS has been applied in semi-arid and other regions to obtain daily, monthly, and annual ET (e.g. Jin et al. 2009). Problems appear in sparsely vegetated drylands. Lubczynski and Gurwin (2005) indicate that SEBS, and other RS based solutions of the surface energy balance, overestimate ET in such areas by 1.5-3.0 $mm \cdot day^{-1}$ due to an underestimation of the sensible heat flux. The first objective of this article is to compare ground measurements of evaporative fraction (EF) from Bowen ratio stations with the EF results of SEBS in the semi-arid Konya closed basin in Turkey, in order to test the previous findings.

The problem with sparsely vegetated dry conditions is mainly related with defining the surface roughness parameters, which directly affect the partitioning of the fluxes. As Verhoef et al. (1997) discuss in detail, it is usually more difficult for the models to obtain suitable roughness parameters from RS for sparse (natural) vegetation than for agricultural crops. Furthermore, the model for thermal roughness itself may not be valid in these conditions, causing the same problem for other single source models (Huntingford et al. 2000).

On the other hand, the relationship between ET and soil moisture is stronger in sparsely vegetated semi-arid regions but the current models do not directly make use of this fact: among others, SEBS uses the land surface temperature to incorporate implicitly all the effects of the soil and interception evaporation, transpiration effected by root water uptake, soil moisture, stomatal regulation and interception storage. The relation between soil moisture and ET is not universal, but it depends on soil type, vegetation type, and vegetation adaptation to drought (Teuling et al. 2006). Despite of the relation's site-specific nature, soil moisture data can complement the SEBS estimates in drylands since the influence of near-surface soil moisture on the partitioning of available energy and thereby on EF is likely to be greater in semi-arid environments (Kustas et al. 1993; Small and Kurc 2003; Wang et al. 2006). The second objective of this study is to develop an alternative method for areas where the single-source energy balance models fail through using the same key RS based input as in SEBS: land surface temperature, NDVI, and an additional variable: soil moisture.

2. STUDY AREA AND DATA DESCRIPTION

The Konya closed basin (KCB) is located in central Anatolia, Turkey, between 37^0 N 31^0 E and 39^0 N 35^0 E. The basin covers an area of around 54 000 km^2 with elevation from 900 to 3500 m.a.s.l. The climate is arid to semi-arid with an average precipitation of 380 mm/year, ranging spatially between 250-800 mm (unpublished data from local water authority). The land cover in the KCB shows a strong contrast between intensively irrigated agricultural lands and the sparse steppe areas in the extensive plains of the mid- and downstream parts. Here, the groundwater is the main source for irrigation, which can easily be accessed in the extensive plains of the basin by means of 50 to 250 m deep wells.

2.1. Bowen ratio stations and data

Five Bowen ratio (BR) stations were installed in the basin, mounting two combined sensors of temperature and relative humidity (Decagon devices, WA, USA) at heights of 0.5 and 2 m at each station. In addition, one soil moisture sensor was installed at 5 cm depth. The values of the parameters were recorded in every 30 min. as the average of per minute measurements. The locations of the BR stations were chosen to account for different land covers and ease of maintenance: BR-1 and 5 are located in agricultural plots (sunflower and potato) that were bare at the time of installation (Oct., 2009). BR- 2 is installed in the downstream salt marshes, where the dominant plant species is bulrush. BR-3 is located in a field where alfalfa is grown in a controlled way and BR-4 is on sparse steppe vegetation. Sandy soils cover the area at both BR-3 and BR-4. The Bowen ratio values (β) were calculated following (Ohmura 1982) and assessed for reliability according to Perez et al. (1999). Incorporating the definitions of Bowen ratio and EF, the relation between them is derived as:

$$EF = 1/(1+\beta) \tag{1}$$

Eq. (1) has the advantage that the relation is independent of the soil heat flux and the accuracy of the net radiation estimates, which makes the interpretation of the results more straightforward.

2.2. SEBS data

The details of SEBS algorithm and how the model solves the surface energy balance terms and EF are presented in Su (2002). In this study, MODIS visible, near infrared and thermal bands were used to retrieve the necessary parameters (e.g. albedo, emissivity, land surface temperature, roughness heights), corresponding to the satellite overpass on October 10^{th} and 12^{th}, November 7^{th}, 23^{rd} and 27^{th} in 2009. Besides the RS data required for SEBS, the daily 0.25 degree surface soil moisture product from AMSR-E observations (Owe et al. 2008) were used in quantifying the EF spatial distribution. Meteorological data including air temperature (hourly and daily), wind speed, air pressure, sunshine hours and incoming solar radiation were obtained from the 18 stations located in the basin. All the relevant data were spatially interpolated. In SEBS, it is assumed that the daily EF is equal to the instantaneous value calculated for the satellite overpass time. Then, the daily evaporation is determined as (Su 2002);

$$E_{daily} = 8.64 \cdot 10^7 \cdot (EF \cdot \overline{R_n} / \lambda \cdot \rho_w) \tag{2}$$

where E_{daily} is actual ET [mm d^{-1}], λ is the latent heat of vaporization, ρ_w is the density of water [kg m^{-3}] and $\overline{R_n}$ is daily net radiation [MJ m^{-2} day^{-1}].

3. RESULTS

3.1. Is SEBS sensitive to low EF values in a semi-arid region?

The EF output by SEBS model (EF_{SEBS}) was compared with the EF ground data (EF_{BREB}) to evaluate how the model can capture the EF observed in sparsely vegetated dry areas. Figure 1 clearly shows that there is a significant bias by the SEBS model compared to the observations by the Bowen ratio system. In fact, the lowest EF_{SEBS} values were around 0.6 corresponding to EF_{BREB} field measurements as low as 0.1.

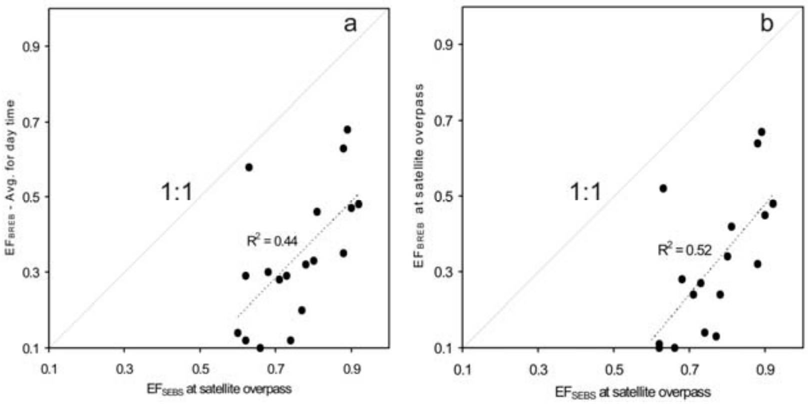

Figure 1. The comparison of EF_{SEBS} (applied to the cloud free MODIS images in Oct. and Nov. 2009 with EF ground measurements from 5 BR stations (daily avg. & at satellite overpass)

3.2. The controlling factors of EF for sparsely vegetated drylands

After revealing that SEBS is not capturing the low range of EF under sparsely vegetated dry conditions, an alternative solution was sought particularly for these areas using the ground measurements of EF from BR-3 and BR-4 since these stations were representative for such conditions and had the same soil types. The results in Figs. 2a and 2b indicate that, in case of sparse vegetation in a semi-arid region, the EF is directly and inversely correlated with soil moisture (SM) and temperature gradient respectively. The relation improves when these two parameters are combined as a ratio (Fig. 2c). Furthermore, if NDVI is added to this ratio to incorporate the vegetation influence on EF and the relation gets even stronger with EF (Fig. 2d).

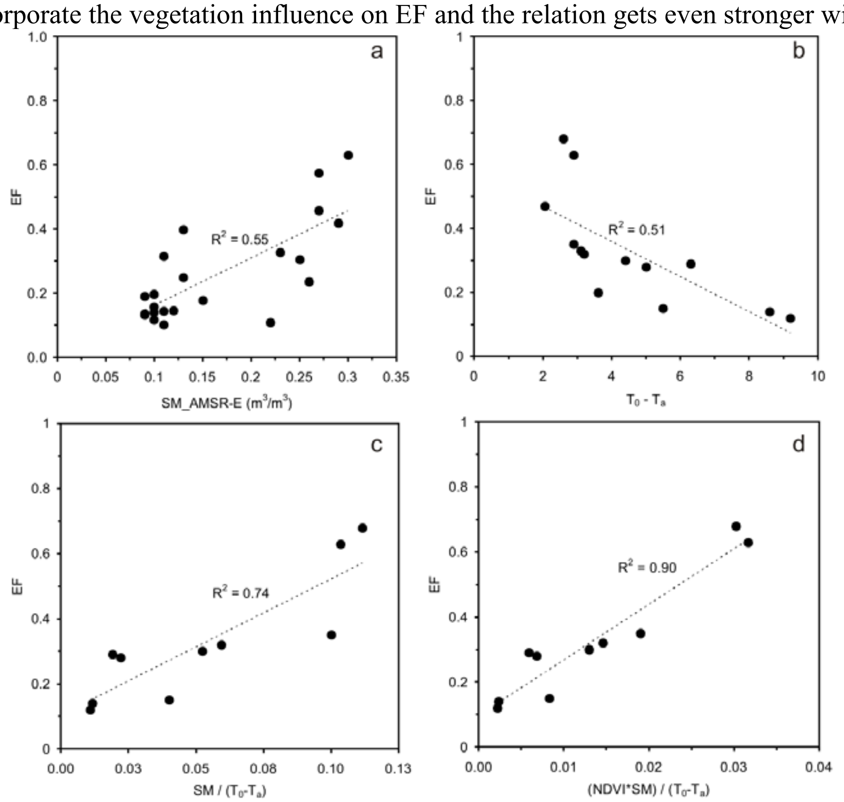

Figure 2. The relation of EF with (a) remote sensing of SM, (b) temperature gradient between land surface and near surface air (T_0-T_a), (c) the ratio of [SM/(T_0–T_a)], and (d) the ratio of [(NDVI*SM)/(T_0–T_a)] under sparsely vegetated dry conditions.

3.3. An improved ET distribution in a semi-arid region

As shown in the scatter plot (Fig. 3a), the cloud of daily ET values of SEBS show a V shape with quite high ET values at the lower range of NDVI, which was confirmed as overestimation in Fig. 1. Also, the daily ET map by SEBS is rather homogeneous. However, Fig. 3b presents an S shape when the empirical relation of EF obtained from Fig. 2d is applied to the pixels with NDVI between 0.0-0.2 and T_0–T_a greater than 5 °C to account for sparsely vegetated dry conditions. The resulting ET map (Fig. 3d) shows a better contrast between high and low ET values (even lower than 1 mm d^{-1}), which is generally observed in semi-arid regions between the irrigated fields and the extremely dry landscape (Gowda et al., 2007).

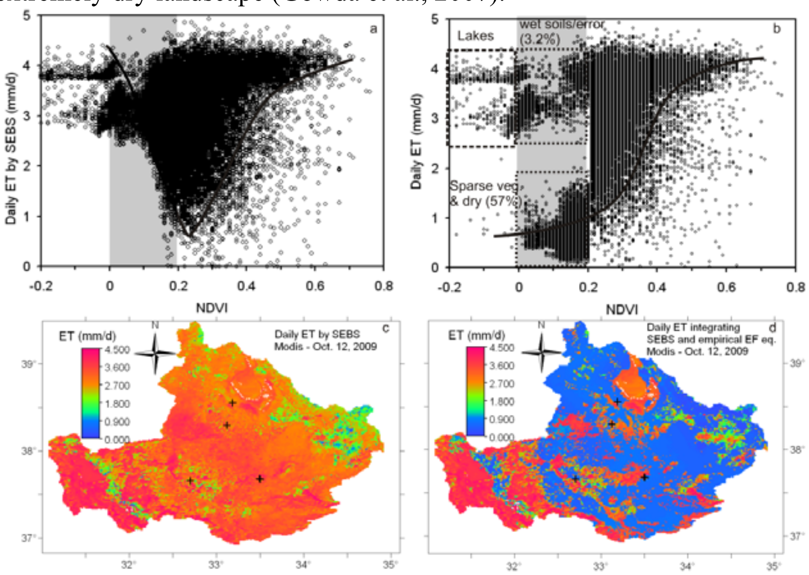

Figure 3. An improved mapping of ET combining SEBS and the empirical function: (a) daily ET of SEBS vs. NDVI, (b) daily ET combining SEBS and empirical func. (Fig. 2d) vs. NDVI, (c) daily ET map of SEBS on Oct. 12, 2009, (d) daily ET map combining SEBS and empirical function (Fig.2d) on Oct. 12, 2009.

4. DISCUSSION AND CONCLUSION

Even physically based surface energy balance models such as SEBS contain empirical relations to estimate roughness lengths or soil heat flux, which can lead to a significant overestimation of EF under sparsely vegetated dry conditions (Fig. 1). Applying a priori values for the roughness length for different land cover classes could be a better approach, however for regional scale studies such as in KCB, the heterogeneity involved in the large pixel size do not allow applying such approaches. Therefore, there is a need for improvement of surface energy balance models for sparse vegetation in semi-arid regions. By this study, we showed how a simple and empirically derived function of soil moisture, T_0-T_a, and NDVI can complement the SEBS for an improved spatial ET distribution in a semi-arid region.

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